Supernova-Neutrino Studies with ^{100}Mo

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Abstract

We show that supernova neutrinos can be studied by observing their charged-current interactions with ^{100}Mo, which has strong spin-isospin giant resonances. Information about both the effective temperature of the electron-neutrino sphere and the oscillation into electron neutrinos of other flavors can be extracted from the electron (inverse β) spectrum. We use measured hadronic charge-exchange spectra and the Quasiparticle Random Phase Approximation to calculate the charged-current response of ^{100}Mo to electron neutrinos from supernovae, with and without the assumption of oscillations. A scaled up version of the MOON detector for $\beta\beta$ and solar-neutrino studies could potentially be useful for spectroscopic studies of supernova neutrinos as well.

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Neutrinos carry away most of the energy from core-collapse supernovae. Supernova neutrinos (SN-ν's) can be observed on the earth, and their spectrum contains information about conditions inside the supernova as well as their own properties. Here we aim to show that ^{100}Mo, which responds strongly to spin-isospin probes, is useful for studying supernova weak processes and SN-ν oscillations, and that a good SN-ν detector can be realized by scaling up the proposed $\beta\beta$ and solar-neutrino detector MOON.

Though there is much we don't know about supernovae, the consensus of modelers is that SN-ν's are released roughly thermally from the supernova remnant after diffusing to the surface of last scattering, called the "neutrino sphere". They therefore escape with an energy corresponding approximately to the thermal energy spectrum at the sphere [1, 2, 3]. In this picture there are really three neutrino spheres, one for electron neutrinos (ν_e's), one for electron antineutrinos ($\bar{\nu}_e$'s), and one for the other flavors (ν_x's and $\bar{\nu}_x$'s). The ν_e sphere has the largest radius of these because ν_e's interact with matter via both charged- and neutral-current reactions. So do $\bar{\nu}_e$'s, but the excess of neutrons over protons in the supernova remnant means that they scatter less frequently through charged-current interactions, so that the radius of their neutrino sphere is smaller. The other neutrinos (ν_x, $\bar{\nu}_x$), with only the neutral-current interactions, decouple deeper within the star. Since the

temperature in the supernova core increases as the radius gets smaller, these last neutrinos will have the highest energy, and the ν_e's the lowest energy.

The SN-ν spectrum for a given neutrino species is thought to be roughly [2] [3]

$$S(E_\nu) = cT_\nu^{-1}\frac{(E_\nu/T_\nu)^2}{\exp(E_\nu/T_\nu - a) + 1} \tag{1}$$

where T_ν is the temperature at the neutrino sphere, a is the degeneracy parameter, and c is a normalization constant. Numerical simulations can be approximately reproduced with temperatures T_ν of about 3.5 MeV for ν_e's, 5 MeV for $\bar{\nu}_e$'s, and 8 MeV for ν_x's and $\bar{\nu}_x$'s, with the degeneracy parameter a taken to vanish. Accordingly, the average ν energies are $< E(\nu_e) >\sim$11 MeV, $< E(\bar{\nu}_e) >\sim$16 MeV, $< E(\nu_x) >\sim$25 MeV, and the spread of SN-ν energies covers the wide region of $E \sim$ 5-70 MeV.

Measuring the ν_e spectra would provide us information on the electron neutrino sphere, and thus tell us if our supernova models are on the right track. It could also tell us about neutrino oscillations; if our ideas about where the neutrinos leave the supernova are correct, ν_e's with energies above 30 MeV or so are rarely emitted directly from the supernova. An excess of high-energy ν_e's reaching the earth would be strong evidence for oscillations from ν_x to ν_e.

A number of detectors can study neutrinos in the event of a nearby supernova. They have the ability to detect either the charged-current ν_e ($\bar{\nu}_e$) interaction, which produces electrons (positrons), or the neutral current interaction (for all flavors), which usually results in the production of neutrons and photons, or both. Antineutrinos from SN1987A were observed by the Kamiokande [4] and IMB [5] groups in water Cerenkov detectors via the reaction $p + \bar{\nu}_e \rightarrow n + e^+$. SuperKamkiokande, with multi tons of water, and the Sudbury Neutrino Observatory (SNO), with kilotons of heavy water, are powerful detectors for SN-ν's (see ref. [6]). SuperKamiokande, however, has a high threshold ($Q \sim$ 15 MeV) for the charged-current interaction of ν_e's with ^{16}O. The effective threshold energy, including a 5-MeV threshold for detecting an electron produced by the charged-current interaction, is therefore about 20 MeV, well above the average energy of neutrinos emitted from the ν_e sphere. As a result, while the detector is good for charged-current $\bar{\nu}_e$ interactions, it will have a hard time saying anything about the flux or energy distribution of thermally emitted ν_e's. Detectors based on liquid scintillator, such as KamLAND [7], also have a high threshold for ν_e charged current interactions with ^{12}C — about 17 MeV, with an effective threshold energy of around 20 MeV. They will not be able to study neutrinos from the ν_e sphere either. SNO, on the other hand has a low threshold, plus the eventual ability to separately measure charged and neutral current interactions.

Ref. [8] shows that information on SN-ν energies and oscillations can be obtained by measuring the number of neutrons produced by neutrino scattering from heavy nuclei. The method is very good for getting gross features of the SN-ν spectra and possible oscillations, and the proposed facilities OMNIS [9], SBNO [10], and LAND [11] are based largely on the detection of neutrons. These detectors cannot easily measure the spectra of charged-current events, however. In addition, the ν_e cross section on lead is small at low energies because of the extreme concentration of Gamow-Teller(GT) strength in a single resonance at high excitation, so that information about low-energy neutrinos will be hard to obtain.

A low-threshold charged-current detector would therefore add to our ability to study neutrinos from the ν_e sphere, particularly if the detector could measure the spectrum of electrons from the neutrino interactions and if it were made of a material with a large SN-ν cross section. If our ideas about the ν_e sphere are grossly wrong, such a detector would also tell us that. By looking for high-energy ν_e's, the detector could also complement existing and planned facilities in studying SN-ν oscillations.

A recent paper [12] argues that MOON (Mo Observatory Of Neutrinos), containing a few tons of ^{100}Mo, would be useful for studies of both $\beta\beta$ decay (having the ability to detect a neutrino mass as low as $< m_\nu >\sim 0.03$ eV) and real time studies of low energy solar-ν spectra. In what follows we discuss how ^{100}Mo and a scaled-up MOON would be useful for studying SN-ν's as well as low energy solar-ν's.

The isotope ^{100}Mo has a threshold (Q value) for the charge-exchange process

$$\nu_e +^{100} \mathrm{Mo} \longrightarrow e^- +^{100} \mathrm{Tc} \tag{2}$$

of only Q=0.17 MeV, much less than other detectors with light nuclei such as ^{12}C and ^{16}O. In addition, one expects ^{100}Mo to exhibit a large response to charged-current interaction of SN-ν's because of the large neutron excess (isospin $T_z \equiv (N-Z)/2 = 8$), which enhances the strengths of spin-isospin giant resonances.

Recent measurements of ^{100}Mo(^{3}He,t)^{100}Tc cross sections [13] confirm this expectation. They show that at energies below 50 MeV this reaction (changing neutrons to protons) primarily excites four isospin giant resonances [14]: the isobaric analog resonance (IAR) with $J^\pi = 0^+$, the Gamow-Teller giant resonance (GTR) with $J^\pi = 1^+$, the isovector dipole resonance (IDR) with $J^\pi = 1^-$, and the isovector spin-dipole resonance (ISDR) with $J^\pi = 0^-, 1^-, 2^-$. The GTR is accompanied by a low-energy shoulder (GTR') below the main peak. The IAR and IDR are excited by operators in coordinate space (times the isospin-raising operator τ_+) while the GTR and ISDR involve the spin operator $\vec{\sigma}$ as well.

The strength in these resonances are spread over the excitation energy region 5-35 MeV, with the centroid of IAR at 11.6 MeV, the GTR and GTR' centroids at 13.4 MeV and 8 MeV, and the centroid of the combined dipole resonances, which cannot be separated by the experiment, at 21 MeV [13]. This energy range corresponds nicely with that of SN-ν's, which will therefore also proceed primarily through the resonances, particularly the GTR. The spread of the GT strength down to below 5 MeV together with the low Q value of the charge-exchange process in eq. (2) make the effective threshold as low as a few MeV, well below the average SN-ν_e energy. As we discuss next, we can actually use the measured charge-exchange response to calibrate a calculation of SN-ν cross sections.

Precise expressions for the matrix elements that govern these cross sections are given in Ref. [15]. We use the charge-changing quasiparticle random phase approximation (QRPA) to calculate most of these matrix elements. Our approach is similar to that of ref. [16] with improvements such as a larger model space (about 20 single-particle levels around the Fermi surface for both protons and neutrons), and a better treatment of the Coulomb interaction of the outgoing electron [17] The interaction we use has the same δ-function form, with parameters adjusted to fit the observed GTR energy and the low-lying spectrum in ^{100}Mo. For neutrinos of the energies we consider here, it is sufficient to include multipoles up to $J = 4$.

In the important 1^+ channel, we replace the QRPA calculation with the measured GT strength. Because the neutrino cross section in this channel is determined mainly by the operator $j_0(qr)\vec{\sigma}\tau_+$, rather than the GT operator $\vec{\sigma}\tau_+$, we must supplement the measured GT strength with a q-dependent form factor. We obtain the form factor from the Helm model [18] , which takes the strength to be peaked at the nuclear surface. We cannot repeat this procedure for higher multipoles because they are not separated in the measured spin-isospin dipole strength distributions (and the overall normalization is not known). Our theoretical strength distributions, however, reproduce the measured ones quite well, up to the unknown normalization constant. We choose not to artificially quench the strength of the dipole transitions because no clear evidence supports such quenching; muon capture, in fact, argues against it [19]. The use experimental data to calibrate these calculation should make them accurate to within a factor of two at worst[1].

Fig. 1 shows the calculated cross section for ν_e scattering on ^{100}Mo as a function of neutrino energy. The charge-changing flux-averaged SN-ν cross sections, broken down by multipole, appear in Table 1. We consider two cases, non-oscillating SN-ν_e's, and SN-ν_x's (either ν_μ's or ν_τ's, but not both) that oscillate completely into ν_e's. We label these two cases by ν_e and ν_{ex}. GT-like transitions, the major part of the 1^+ contribution, dominate the cross section, particularly for the non-oscillating ν_e's, which have lower energy on average. The cross section for ν_{ex}'s is more than an order of magnitude larger than that for non-oscillating ν_e's. Since ν_x's have energies well above the GT and dipole giant resonances, the phase space for ν_{ex} scattering is quite large.

Fig. 2 shows the calculated spectra (or counts per MeV ton of ^{100}Mo) of electrons produced by the charged-current interactions of both ν_e and ν_{ex} from a typical supernova 10 kpc away, emitting 3×10^{53} ergs. We assume that the SN energy is partitioned equally among all neutrino flavors. The average electron energy of 25 MeV for ν_{ex} is about 2.5 times larger than the average energy of 11 MeV for ν_e, reflecting the ratio of temperatures at the two neutrino spheres. This means that the flux of ν_e's is higher by the same factor, a fact reflected in the count rates.

The large electron energy for ν_{ex}, together with the large cross section, make a ν_{ex} component clearly visible; the observation of a large fraction of the events at relatively high electron energies would be a clear signal of oscillations. But the figure also tells us about the importance of a low threshold. In a large enough detector, the neutrinos from the ν_e sphere will clearly be observable if there are no oscillations. If there is a resonant effect that converts all ν_e's into ν_x's then, of course, no detector will tell us anything about the ν_e sphere. But if — as in the solution to the solar and atmospheric neutrino problems with large θ_{12} and $\theta_{13} = 0$ — half of the emitted ν_e's oscillate into ν_x's, the number of events from ν_e relative to that from ν_{ex} will be the same as shown in the figure. At energies below 10 or 15 MeV, a significant fraction of the events would come therefore from the ν_e sphere, and one could learn something about the spectrum of emitted ν_e's even in the presence of oscillations.

How large a detector would we need? Our calculations imply that with a supernova 10

[1]Our cross sections for the highest-energy neutrinos may be slightly too small because of the restrctions on our single-particle space.

kpc away emitting 3×10^{53} ergs, one would detect about 2 ν_e's and about 13 ν_{ex}'s (under the no-oscillation and maximum-oscillation scenarios discussed above) in a detector with 30 tons of ^{100}Mo. Such a detector is roughly equivalent to the MOON detector discussed in ref. [12], which contains 3.3 tons of ^{100}Mo, corresponding to 34 tons of natural molybdenum; we argue below that the cross sections on other molybdenum isotopes will be of the same order as in ^{100}Mo. Thus, even as proposed MOON could conclusively answer the question of whether there are oscillations from ν_x to ν_e. One would need a detector at least an order of magnitude larger, however, to look closely at the spectrum of non-oscillating ν_e's, and thus the characteristics of the electron neutrino sphere.

The proposed MOON detector could be realized either as a supermodule of plastic scintillators with thin natural or enriched molybdenum layers or a liquid scintillator doped with natural or enriched molybdenum. The former design can be scaled up to a kiloton of natural molybdenum by increasing the Mo thickness of the modules from of 0.03 g/cm^2 to 2 g/cm^2 ($\sim$1mm). The average energy loss in the foil is only 1.7 MeV for the electron from (ν_e, e). Thus the effective threshold energy (Q value + detector threshold energy) could still as low as 2 MeV, far below the average energy of the ν_e's.

The cross-section of SN-ν_e's per unit weight for ^{100}Mo is about as large as that for ^{208}Pb because of the large neutron excess $(N-Z)/A = 0.16$ and the small thereshold energy. What are the effects of using natural molybdenum rather than ^{100}Mo? As Table 1 suggests, the non-oscillating ν_e's mainly excite the GT resonance, so that their cross sections are very roughly given by the product of the GT strength $B(GT)$ and a phase space factor G. The GT strength is roughly proportional to T_z and G is proportional to $(E_\nu - Q_G)^2$, where E_ν is the effective neutrino energy and Q_G the Q value for exciting the GT resonance. Q_G has a slight linear dependence on T_z [14] [20]. These facts imply that the use of natural Mo with the T_z $\sim$6 (on average) will reduce the ν_e count rate by something on the order of 35% from the rate in ^{100}Mo, which has $T_z = 8$. The ν_{ex}'s excite all the resonances discussed above, but the strength associated with those also depends linearly on T_z. If we assume that the energies of those resonances scale the same way as that of the GT resonance, we find that the count rates in natural molybdenum for the high-enegy neutrinos are perhaps 30% smaller than in ^{100}Mo. The Q values for the ground state transitions are just a few MeV higher for other Mo isotopes than for ^{100}Mo. Thus a detector with natural Mo can still have a low effective threshold, and efficiencies of the same order as those with ^{100}Mo. Such a detector could therefore serve our purpose: providing useful information about the spectrum at the electron-neutrino sphere, as well as observing oscillations and measuring the effective temperature at the ν_x sphere. And if our ideas about the emission of neutrinos by supenovae are wrong, the detector would be sensitive enough to tell us so.

Mo, which has a large neutron excess, is not so sensitive to antineutrinos because most of the GT transitions are Pauli blocked. Neutral-current interactions of SN-ν's would excite the Mo isotopes, which decay mostly by emitting neutrons and successive γ rays. These particles deposit energy in a large volume of scintillator, and so could be separated from charged-current events, which have a single electron signal accompanied by several neutron and γ signals. But other detectors, such as SK and SNO, would see more neutral current events (and many more antineutrino-charged-current events) than this one would

[6, 21]. A Mo detector, with its sensitivity to ν_e's, would therefore not obviate other detectors, but would complement them nicely. Information on the antineutrino spectrum, for example, could strengthen evidence for oscillations that might be observed in the neutrino spectrum.

In summary, ^{100}Mo and other Mo isotopes have large cross sections for SN-ν_e and SN-ν_{ex}. A scaled up version of MOON, which could measure electron energy spectra down to $\sim$ 2 MeV, would be useful both for studying neutrino oscillations and for learning about conditions at the electron-neutrino sphere. With the exception of SNO, which has an effective threshold of few MeV, no other detector could do the latter as well. Other heavy nuclei with large $N - Z$ could conceivably be used in place of molybdenum in the liquid-scintillator version of the detector.

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Table 1: Calculated flux-averaged neutrino cross sections in units of 10^{-41} cm^2, with contributions from each multipole given separately

	ν_e	ν_{ex}
0^+	0.65	8.94
0^-	0.02	0.59
1^+	4.62	32.34
1^-	0.14	11.86
2^+	0.04	4.62
2^-	0.34	14.00
3^+	0.03	3.78
3^-	—	1.00
4^+	—	0.23
4^-	—	0.79
total	5.84	78.16

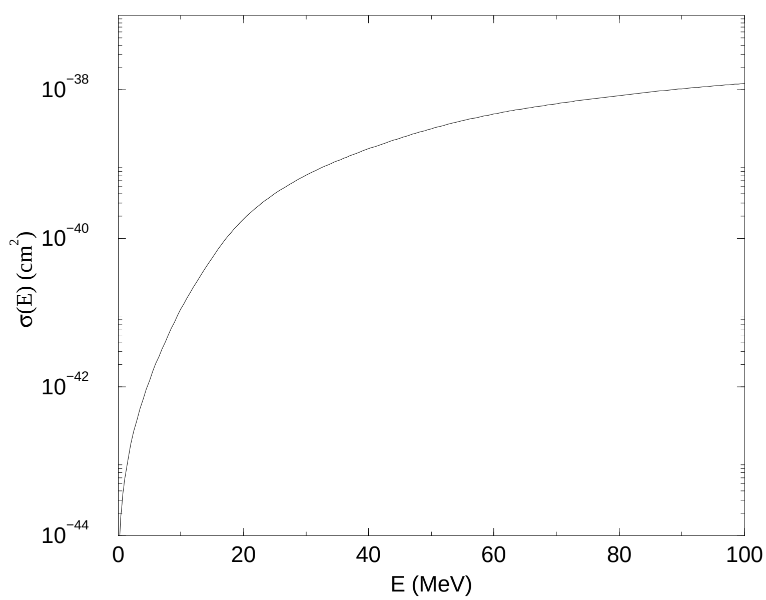

Figure 1: The calculated cross section for ν_e charged-current scattering on ^{100}Mo, as a function of neutrino energy.

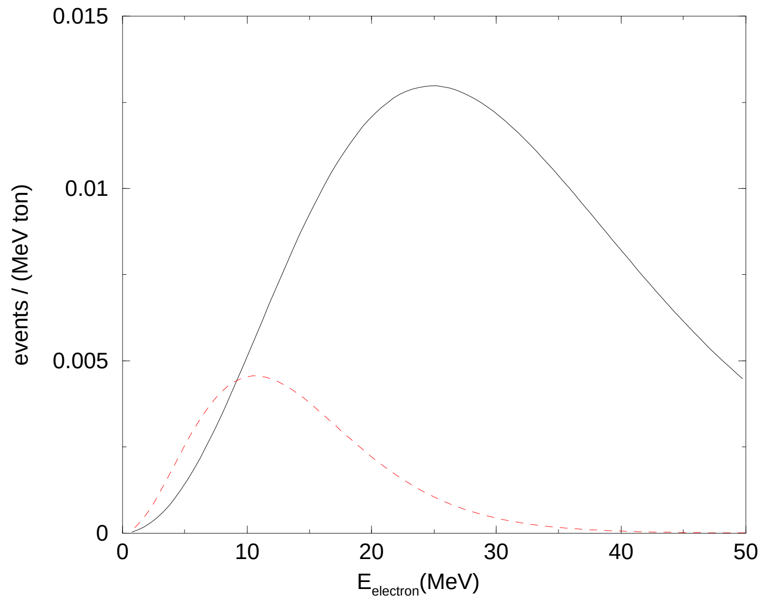

Figure 2: The calculated energy spectra of electrons produced by charged-current interactions of both ν_e (dashed line) and ν_{ex} (solid line), assuming equipartition of SN energy among all flavors. The vertical axis is the number of electrons per MeV per ton of ^{100}Mo.